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Plastic collapse of cylindrical shell-plate periodic honeycombs under uniaxial compression: experimental and numerical analyses

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ABSTRACT

This paper studies the plastic collapse mechanisms of uniaxially-loaded cylindrical shell-plate periodic honeycombs with identical mass (or relative density) but varying geometric parameters, by series of in-plane and out-of-plane experiments and finite element numerical simulations. The coupled experimental-numerical results show that mechanical properties of the honeycomb can be optimized in all three loading cases, thanks to the complementary changes of the mechanical properties of cylindrical shell and plate as the geometric parameters vary. The work presents a concept to optimize lattice structures by combining different substructures, and can be used in designing new low-density honeycomb structures with desired mechanical requirements but less base materials and weight.

1. Introduction

Honeycomb and foamy structures widely exist in natural materials (*e.g.*, *Luffa* sponge [1]), which are shaped by their surrounding environment. In view of optimization in the process of natural evolution, it facilitates the study of the natural or man-made foamy materials with multiple functions, such as energy-absorption [2], heat-transfer [3,4] and electromagnetic absorption [5]. To date, varieties of honeycomb structures are presented. From the point of view of mechanics, the conventional hexagon, square, triangle, Kagome honeycombs [6] or 3D topological lattices [7] have been widely studied, and their collapse mechanisms clearly described [8–10]. These studies have already been used as guidance for the design of porous materials.

As the importance of hierarchical strategy in natural materials is gradually realized, hierarchical honeycomb and foamy structures are also constructed and studied. In general, as the porosity of the structure increases, reducing the relative density of the structure, their mechanical properties decrease (*e.g.*, critical buckling load [11]). However, if a hierarchical structure is designed with a constant amount of bulk materials, its mechanical properties, such as Young's modulus and strength [12], can be optimized by replacing solid cell walls [13–15] or joints [16,17] of conventional single-level honeycombs with porous substructures. In the case of the solid cell walls replaced by porous substructures, the bending rigidity of the cell walls is increased because of the increased porous cell-wall thickness [12,18], and in the other case, *i.e.*, joints replaced by porous substructures, the failure modes of the cell walls and porous joints are interchanged [19]. It is worth mentioning that when the hierarchical level comes down into the nanoscale, the surfaces effect has to be taken into account [20,21].

To look for new and more efficient honeycomb structures, very recently, the authors presented a cylindrical shell-plate assembled periodic (or so-called hollow-cylindrical-joint) honeycomb (Fig. 1) [19], which actually derives from the family of center-symmetrical honeycombs [22], and analytically studied its Young's modulus, Poisson's ratio, fracture strength and toughness in the x direction. Moreover, they reported that the mechanical properties of the structure were optimized and improved compared to the conventional hexagonal honeycombs, thanks to the variation of

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structural styles. But the work only dealt with the in-plane mechanical properties in the x direction *via* a theoretical approach [19]. Then, questions rise: what about the in-plane mechanical properties in the y direction and out-of-plane mechanical properties? Are they also optimized?

In order to thoroughly describe the mechanical behaviours of the assembled periodic honeycomb, we here continued the study of the honeycomb by coupling experiments and numerical simulations. First, two sets of quasi-static crushing experiments (six in-plane samples with eight unit cells loaded in the x, y directions, Fig. 1a, and five out-of-plane samples with three unit cells in the z direction, Fig. 1b) were performed. Plastic collapse processes of selected samples and stress–strain curves of all samples were recorded. Second, non-linear finite element method (FEM) numerical simulations were employed to deeply reveal plastic and fracture behaviours and stress states, which were not visually identifiable with the experiments. Finally, the collapse mechanisms were discussed.

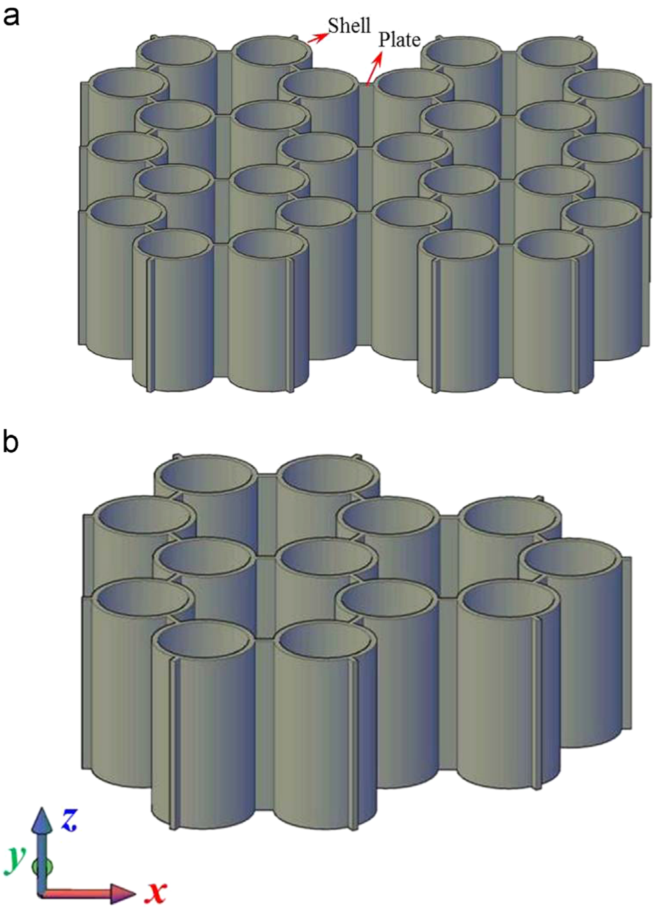


Fig. 1. Images of (a) an in-plane loaded sample and (b) an out-of-plane loaded sample.

2. Methods

2.1. Experiments

Using 6061-T4 aluminum alloy as the bulk constituent material, eleven honeycomb samples with a controlled dimensional error 0.03 mm in thickness, were fabricated by Nanjing Siyou Photoelectric Technology Limited, Nanjing, China.

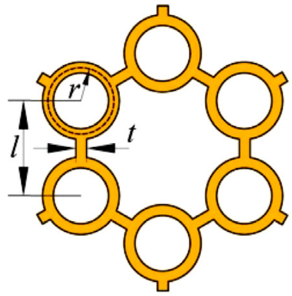
In the design of the samples, the samples had theoretically identical relative density $\rho^*/\rho^c = 0.1$, in which $\rho^* = 0.27\ \text{g/cm}^3$ and $\rho^c = 2.7\ \text{g/cm}^3$ are the densities of the honeycomb and the bulk aluminum alloy, respectively. The sizes in z direction were 20 mm and 30 mm for the in-plane and out-of-plane samples, respectively, and the distance l between centres of two adjacent cylindrical shells was fixed to be 20 mm. The radius r of the cylindrical shell was first selected, and the wall thickness t was determined by the following equation $\rho^*/\rho^c = -1.155\cdot(t/l)^2 + [2.528\cdot(r/l) + 1.155]\cdot(t/l)$ [19], and the masses of the models were calculated by multiplying the volumes of the samples to their density $\rho^* = 0.27$, see Table 1.

Actually, their real masses m_{re} are lower, see Table 1. Moreover, according to the design, the masses of the in-plane samples should theoretically be equal, and also for the out-of-plane ones, here the mass difference is due to the samples' processing.

The samples were tested under uniaxial compression with a 1000HDX Instron Universal Testing Machine (ITW, USA) with loading capacity of 1000 kN. Before testing, in order to ensure the samples to be loaded uniformly, two steel plates were respectively placed at the top and bottom surfaces of the samples. The whole loading process was displacement controlled from the bottom up. For the in-plane samples, considering their larger size along the loading direction, a short linear-elastic stage of stress–strain curves and limit influence of loading rate on the plastic collapse stage were expected; thus, the loading rates before and after the initial yield of the samples were set to be 1 mm/min and 10 mm/min, respectively. For the out-of-plane samples, the loading rate was kept constant at 1 mm/min.

Regarding the definitions of stress and strain of the compressed honeycombs in the experiments, the stress was calculated as

Table 1
Geometric parameters and masses (m) of the samples. The numbers in the brackets denote the masses of the samples compressed in the y direction.

		In-plane loaded samples						Out-of-plane loaded samples					
	r/l	n.	l [mm]	r [mm]	t [mm]	m [g]	m_{re} [g]	n.	l [mm]	r [mm]	t [mm]	m [g]	m_{re} [g]
	0.0	—	—	—	—	—	—	1	20	0	1.78	41.7	39.6
	0.2	1	20	4	1.26	59.9	55.8 (53.1)	2	20	4	1.26	41.7	38.9
	0.3	2	20	6	1.08	59.9	55.0 (52.3)	3	20	6	1.08	41.7	39.8
	0.4	3	20	8	0.95	59.9	56.7 (53.2)	4	20	8	0.95	41.7	36.5
	0.5	—	—	—	—	—	—	5	20	10	0.84	41.7	34.6